

# Evaluation of Reactivity for Nitroxide Radical Trapping by Correlation Analysis Using Steric Substituent Parameter ( $\Omega_s$ )

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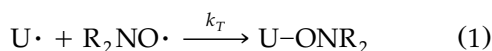
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**ABSTRACT:** The reactivity of nitroxide radical trapping (NRT), where stable nitroxide radicals react with transient carbon-centered radicals to form diamagnetic molecules, was evaluated. This was done with the use of the steric substituent parameter of both radicals by correlation analysis on the basis of the reactivity data determined by Ingold's group. In the case where the transient carbon-centered radicals were not resonance stabilized, the rate constant could be well correlated by using only  $\Omega_s$  parameters of  $R_2NO\cdot$  and  $U\cdot$ . If the transient radicals were stabilized by resonance, the parameter to estimate the amount of the resonance stabilization of  $U\cdot$  was necessary in the regression equation to evaluate the reactivity correctly. When the spin density, calculated by PM3 UHF molecular orbital calculations, was used as the resonance stabilization parameter, the rate constant could be well evaluated by a dual-parameter regression equation. © 1998 John Wiley & Sons, Inc. *J Comput Chem* **19**: 215–221, 1998.

**Keywords:** nitroxide radical trapping; steric substituent parameter  $\Omega_s$ ; molecular mechanics; correlation analysis; reactivity

## Introduction

The radical reactions in which short-lived reactive radical species are involved proceed rapidly and can be monitored only by using sophisticated laser flash photolysis and/or kinetic competition product studies. Therefore, it is rather difficult to determine the rate constants ( $k_T$ ) for various reactions involving transient radical species. In addition, substituent effects for these radical reactions could not be studied in detail because the proper substituent parameters representing the steric and electronic effects were not available for the radical species. We have developed a steric substituent parameter,  $\Omega_s$ ,<sup>1</sup> based on the geometries calculated by molecular mechanics and extensively studied its applicability to various types of reactions.<sup>2</sup>  $\Omega_s$  is defined as the ratio of the shadow area of the substituent projected on the circumscribing sphere to the total surface area. It is of interest to determine whether the  $\Omega_s$  parameters for radical species can also be applied to evaluate the reactivity of radical reactions. As the MM2/MM3 force field parameters have already been determined for carbon-centered radicals<sup>3</sup> and nitroxide radicals,<sup>4</sup> the  $\Omega_s$  values for these radical species can be calculated by using the OMEGAS90 program developed by our group.<sup>5</sup> Ingold's group has studied the kinetics of nitroxide radical trapping (NRT) [eq. (1)] extensively by using the radical "clock" method and by the laser flash photolysis (LFP) technique and reported the structural effects<sup>6</sup> and solvent effects<sup>7</sup> so that:



where  $U\cdot$  and  $R_2NO\cdot$  are the transient carbon-centered radicals and persistent nitroxide radicals, respectively.

Ingold concluded from the kinetic results that the rate constant,  $k_T$ , for this NRT (nitroxide radical trapping) reaction depends upon the steric hindrance to coupling and upon the extent of resonance stabilization of the carbon radical. It is of interest to observe whether the steric effect on  $k_T$  for the NRT reaction can be evaluated by using steric parameter  $\Omega_s$  for the radical species. If the validity of  $\Omega_s$  for the radical species is verified, and the  $k_T$  values can be correlated with  $\Omega_s$ , then it provides a way to estimate the reactivity for the other radical reactions by the use of the  $\Omega_s$  param-

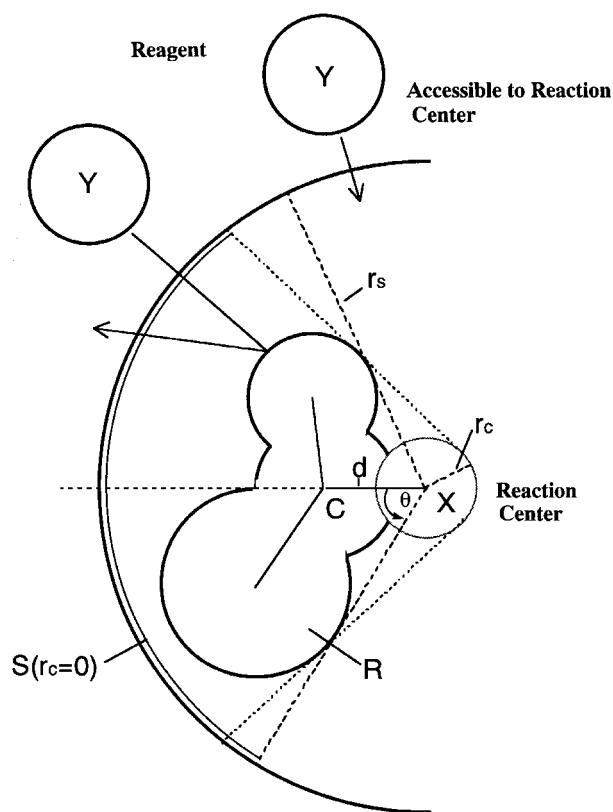
eter. Not only for the NRT reactions, but also for the other reactions involving the radical species, such as spin trapping reactions, the steric effect on reactivity seems to be evaluated correctly by the correlation analysis of use of  $\Omega_s$  parameters.

In this report, an attempt to evaluate the reactivity ( $k_T$ ) of the NRT reaction by using the correlation analysis with the aid of steric parameter  $\Omega_s$  is made and the applicability and the usefulness of the kind of correlation analysis is discussed.

## Theory

### CALCULATION OF $\Omega_s$ FOR THE TRANSIENT CARBON-CENTERED RADICAL ( $U\cdot$ ) AND NITROXIDE RADICAL ( $R_2NO\cdot$ )

To calculate the  $\Omega_s$  for the radicals, the locations of the reaction center atoms for the carbon-centered radical and the nitroxide radical must first be determined. The reaction center atom (X)

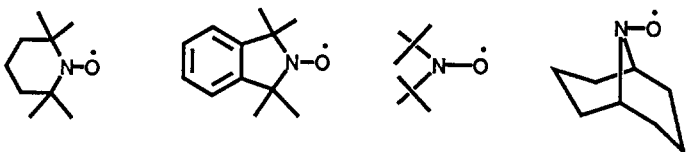


**FIGURE 1.** Definition of steric substituent parameter,  $\Omega_s$ .

$$\Omega_s = \frac{\text{Shadow area of substituent}}{\text{Total surface area}}.$$

TABLE I.

 Rate Constants,  $10^{-7} k_T / (M^{-1} s^{-1})$ , for Nitroxide Radical Trapping at  $18 \pm 2^\circ C$  and Steric Substituent Parameter  $\Omega_s$  of Nitroxide and Carbon-Centered Radicals.

No.	Radical U· structure	<div>  </div>			
		Tempo (0.479)	TMIO (0.433)	DBNO (0.501)	ABNO (0.359)
1.	$CH_3(CH_2)_7\dot{C}H_2$ ( <b>0.263</b> )	123 ± 26 (116)	128 ± 31 (193)	108 ± 28 (92.2)	216 ± 41 (433)
2.	$(CH_3)_3C\dot{C}H_2$ ( <b>0.346</b> )	106 ± 35 (94.5)	112 ± 32 (157)	89 ± 36 (75.0)	202 ± 39 (351)
3.	$(CH_3)_2C\dot{C}H_2C(CH_3)\dot{C}H_2$ ( <b>0.362</b> )	106 ± 35 (91.1)	121 ± 40 (152)		191 ± 32 (339)
4.	$H_2C\dot{C}H_2\dot{C}H$ ( <b>0.308</b> )	210 ± 26 (108)			296 ± 34 (401)
5.	$H_2C(CH_2)_2\dot{C}H$ ( <b>0.380</b> )	141 ± 28 (89.7)			
6.	$H_2C(CH_2)_3\dot{C}H$ ( <b>0.437</b> )	102 ± 21 (76.7)	121 ± 31 (128)		178 ± 40 (286)
7.	$H_2C(CH_2)_4\dot{C}H$ ( <b>0.482</b> )	95 ± 22 (69.1)	103 ± 28 (115)	76 ± 29 (54.9)	172 ± 42 (257)
8.	$(CH_3)_3\dot{C}$ ( <b>0.610</b> )	68 ± 17 (51.5)	91 ± 21 (85.7)	68 ± 18 (40.8)	165 ± 39 (192)
9.	$H_2C=C(CH_3)CH_2\dot{C}(CH_3)_2$ ( <b>0.680</b> )	52 ± 12 (43.7)		46 ± 13 (34.7)	160 ± 51 (163)
10.	$C_6H_5\dot{C}H_2$ ( <b>0.249</b> )	48 ± 8 (19.2)	55 ± 5 (32.0)	46 ± 4 (15.3)	118 ± 9 (71.6)
11.	1-Naphthyl- $\dot{C}H_2$ ( <b>0.289</b> )	8.2 ± 0.2 (13.1)	9.1 ± 1.8 (21.8)		76 ± 5 (48.8)
12.	2-naphthyl- $\dot{C}H_2$ ( <b>0.250</b> )	5.7 ± 1.8 (10.1)	8.2 ± 1.9 (16.8)		81 ± 30 (37.7)
13.	$C_6H_5\dot{C}HCH_3$ ( <b>0.452</b> )	16 ± 4 (19.8)	30 ± 11 (33.0)		86 ± 18 (73.8)
14.	$C_6H_5\dot{C}HCH=CH(CH_3)_2$ ( <b>0.475</b> )	1.9 ± 0.4 (6.79)			90 ± 12 (25.3)
15.	$C_6H_5CH\dot{C}HCH_2\dot{C}H_2$ ( <b>0.521</b> )	10 ± 1 (13.9)			78 ± 12 (51.9)
16.	$C_6H_5\dot{C}(CH_3)_2$ ( <b>0.651</b> )	11.8 ± 0.1 (8.92)	17 ± 3 (14.8)	6.2 ± 0.3 (7.08)	133 ± 8 (33.2)
17.	$(C_6H_5)_2\dot{C}H$ ( <b>0.497</b> )	4.6 ± 0.02 (11.3)	7.7 ± 0.9 (18.8)		82 ± 4 (42.0)
18.	$(C_6H_5)_2\dot{C}CH_3$ ( <b>0.702</b> )	4.5 ± 0.47			
19.	$(C_6H_5)_2\dot{C}CH_2OC(CH_3)_3$ ( <b>0.704</b> )	4.2 ± 0.7 (6.76)	5.6 ± 0.5 (11.3)	3.0 ± 0.4 (5.37)	59 ± 5 (25.1)
20.	$(C_6H_5)_3\dot{C}$ ( <b>0.741</b> )	< 0.1	< 0.1		12 ± 3 (4.85)

Tempo: (2,2,6,6-tetramethylpiperidin-1-oxyl); TMIO: (1,1,3,3-tetramethylisindoline-2-oxyl); DBNO: (di-*tert*-butyl nitroxides); ABNO: (9-azabicyclo[3.3.1]nonane-*N*-oxyl). The rate constants,  $k_T$ , determined experimentally by Ingold's group<sup>6</sup> and the values derived by the correlation [eq. 6] (in parentheses) are shown. Numbers designated by bold letters in parentheses are the values of the steric substituent parameter,  $\Omega_s$ , of the corresponding nitroxides and carbon-centered radicals.

is located at the center of a sphere with the appropriate radius ( $r_s$ ) for projection, and a light source is placed at this reaction center (Fig. 1). For the carbon-centered radical, the reaction center was seen to be a carbon atom on which an unpaired electron was localized; in the case of the nitroxide radical, a nitroxide oxygen atom was placed at the reaction center. After placing the radical molecules as shown in Figure 1, the shadow area projected on the sphere arising from the remaining part (R) of the radical molecules was calculated from the geometry optimized by the molecular mechanics methods MM2<sup>8</sup>/MM3<sup>9</sup>, assuming that each com-

prising atom has a sphere of van der Waals radii.<sup>10</sup> The  $\Omega_s$  values were calculated by using the OMEGAS90<sup>5</sup> program. To evaluate the steric effect of U· and R<sub>2</sub>NO· molecules accurately, every possible stable conformation was searched and its contribution was taken into account by summing the population-weighted  $\Omega_s$  value for each stable conformer. Stable conformations within the range of 2 kcal in steric energy relative to the most stable conformer were searched by using the CONFLEX3<sup>11</sup> program combined with the MM2/MM3 program. The values for the radii of reaction centers ( $r_c$ ) and of the projection spheres

( $r_s$ ), which are optional parameters in calculating  $\Omega_s$ ,  $r_c = 0.0$  Å, and  $r_s = 4.0$  Å, were used in the OMEGAS90 calculations.

The  $\Omega_s$  values were calculated for 20 transient carbon-centered radicals for four stable nitroxides (Tempo: 2,2,6,6-tetramethylpiperidin-1-oxyl; TMIO: 1,1,3,3-tetramethylisoindoline-2-oxyl; DBNO: di-*tert*-butylnitroxyl; ABNO: 9-azabicyclo[3.3.1]nonane-*N*-oxyl), which were used in the NRT experiments by Ingold's group.<sup>6</sup>

#### PARAMETER FOR EVALUATING EXTENT OF RESONANCE STABILIZATION OF CARBON-CENTERED RADICALS

To evaluate properly the reactivity of resonance-stabilized carbon radicals, it was necessary to evaluate the spin density on the carbon atom of the reaction center because the unpaired electron in these radicals is delocalized. Larger spin density on the reaction center atom will enhance the reactivity of the NRT reaction. Spin density values can be estimated experimentally from the ESR hyperfine splitting constant with an H atom attached to the radical center carbon atom ( $a^H$ ) or theoretically by the UHF (unrestricted Hartree-Fock) molecular orbital calculations. Because the H hyperfine splitting constants ( $a^H$ ) for all resonance-stabilized carbon radicals used by Ingold's group were not available in the literature, we estimated the spin density from the semiempirical molecular orbital calculations using the MOPAC6 package. The geometry of the most stable conformation was searched by the MM3 calculations. By using this optimized structure as the input data, spin density was calculated by the UHF method with the PM3 Hamiltonian.

#### CORRELATION ANALYSIS FOR EVALUATING REACTIVITY FOR NRT REACTION BY USING STERIC ( $\Omega_s$ ) AND RESONANCE STABILIZATION [ $\rho(U\cdot)$ ] PARAMETERS OF RADICALS

The rate constants ( $k_T$ ) for NRT reactions, determined experimentally by Ingold's group were correlated with the  $\Omega_s$  of the nitroxide radical  $\Omega_s(R_2NO\cdot)$ , and the carbon-centered radical,  $\Omega_s(U\cdot)$ , in the first step, as shown in eq. (2):

$$\log k_T = a \Omega_s(R_2NO\cdot) + b \Omega_s(U\cdot) + d \quad (2)$$

where coefficients  $a$ ,  $b$ , and  $d$  and the correlation coefficient  $r$  were calculated using the least-squares method.

In the next step, the term representing the extent of the resonance stabilization of the carbon-centered radical  $\rho(U\cdot)$  was added to eq. (2), and the reactivity dependence of the NRT reaction upon the steric effect and upon the extent of the resonance stabilization of the relevant radicals was investigated by using the correlation equation [eq. (3)]:

$$\log k_T = a \Omega_s(R_2NO\cdot) + b \Omega_s(U\cdot) + c \rho(U\cdot) + d \quad (3)$$

In the analysis, all  $\rho(U\cdot)$  values for the radicals with no resonance stabilization were assumed to be 1.

## Results and Discussion

#### STERIC SUBSTITUENT PARAMETER $\Omega_s$ FOR NITROXIDE AND CARBON-CENTERED RADICALS

The calculated  $\Omega_s$  values for the 4 nitroxides and 20 transient carbon-centered radicals are given in Table I, together with the rate constants  $k_T$  for the NRT reaction determined by Ingold's group. It should be observed that the order of ranking of the four nitroxide radicals estimated by the  $\Omega_s$  values was consistent with the experimentally determined kinetic results for the NRT reaction. If the  $k_T$  of the four nitroxide radicals against one transient carbon-centered radical are compared,  $k_T$  is the largest for 9-azabicyclo[3.3.1]nonane-*N*-oxyl (ABNO), and decreases in the order: 1,1,3,3-tetramethylisoindoline-2-oxyl (TMIO); 2,2,6,6-tetramethylpiperidine (Tempo); di-*tert*-butylnitroxyl (DBNO). The  $\Omega_s$  values for these nitroxides vary in the order:  $\Omega_s$  (ABNO);  $0.359 < \Omega_s$  (TMIO);  $0.433 < \Omega_s$  (Tempo);  $0.479 < \Omega_s$  (DBNO); 0.501. In the case where the steric hindrance of the nitroxide is small, the experimentally determined  $k_T$  takes on a larger value. The varying trend of  $k_T$  by the change of  $\Omega_s(R_2NO\cdot)$  among the four nitroxides demonstrates that the rate of NRT reaction was retarded by the steric hindrance around the nitroxide radical center. The  $\Omega_s$  parameters of nitroxides seem to have been evaluated fairly well in a steric sense, although the MM2 parameters for the nitroxides were determined by our group and were not optimized completely. As for the  $\Omega_s$  values of the carbon-centered radicals, the MM3 parameters had already been established as reli-

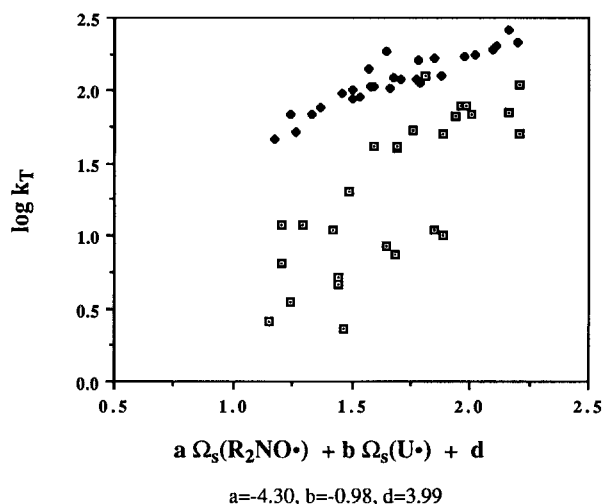
able parameters by Dr. N. L. Allinger.<sup>9</sup> The  $\Omega_s$  values for the 20 carbon radicals used in the experiment varied in the range of 0.249 [10·; C<sub>6</sub>H<sub>5</sub>CH<sub>2</sub>] to 0.741 [20·; (C<sub>6</sub>H<sub>5</sub>)<sub>3</sub>C] from our present study. As the bulkiness of the nitroxide and carbon-centered radicals seem to have been evaluated well by using the  $\Omega_s$  parameter, the reactivity of the NRT reaction could be estimated accurately by correlation analysis.

### CORRELATION ANALYSIS BY STERIC SUBSTITUENT PARAMETER $\Omega_s$ OF NITROXIDE AND CARBON-CENTERED RADICALS

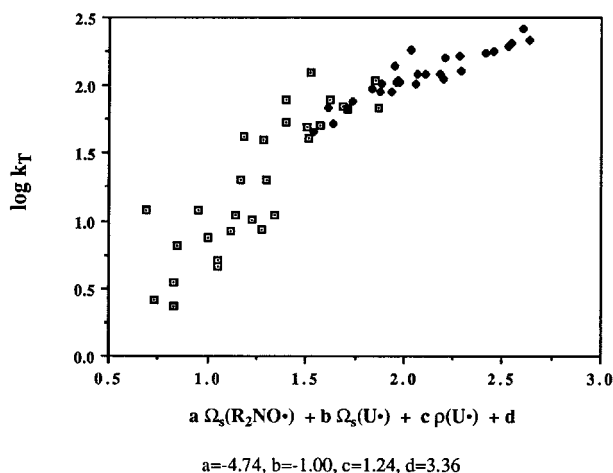
By using the calculated  $\Omega_s$  values shown in Table I, the experimentally determined  $k_T$  values were correlated with the steric substituent parameter  $\Omega_s$  of the nitroxide (R<sub>2</sub>NO·) and carbon-centered (U·) radicals in the form of the correlation equation [eq. (2)]. The best-fit regression coefficients,  $a$ ,  $b$ , and  $d$  in eq. (2), and the correlation coefficient,  $r$  for the 57  $k_T$  data, were as follows:

$$a = -4.30, \quad b = -0.98, \quad d = 3.99, \quad r = 0.53$$

The correlation plot of  $\log k_T$  vs.  $a\Omega_s(\text{R}_2\text{NO}\cdot) + b\Omega_s(\text{U}\cdot) + d$  is shown in Figure 2. The correlation was very poor for the correlation eq. (2), as easily seen from the scattered points in Figure 2. However, it is noteworthy that there exist two different kinds of data groups in Figure 2. One is the group for the carbon-centered radicals without resonance



**FIGURE 2.** Correlation analysis plot using the steric substituent parameters of nitroxides and carbon-centered radicals [i.e.,  $\log k_T$  vs.  $a\Omega_s(\text{R}_2\text{NO}\cdot) + b\Omega_s(\text{U}\cdot) + d$ ]. Boxes = conjugated; filled diamonds = nonconjugated.



**FIGURE 3.** Correlation analysis plot using the steric parameters,  $\Omega_s(\text{R}_2\text{NO}\cdot)$  and  $\Omega_s(\text{U}\cdot)$ , and resonance stabilization parameter,  $\rho(\text{U}\cdot)$ , of carbon-centered radicals [i.e.,  $\log k_T$  vs.  $a\Omega_s(\text{R}_2\text{NO}\cdot) + b\Omega_s(\text{U}\cdot) + c\rho(\text{U}\cdot) + d$ ]. Boxes = conjugated; filled diamonds = nonconjugated.

stabilization for which the data points (filled diamonds in Fig. 2) seem to lie in the linear regression lines. The other group contains the resonance-stabilized radicals for which the data points (open squares in Fig. 2) are scattered. When the linear regression analysis was carried out on just the group containing the carbon-centered radicals without resonance stabilization (28  $k_T$  data), a good correlation was obtained and the correlation equation was described as follows [Eq. (4)]:

$$\begin{aligned} \log k_T = & (-2.46 \pm 0.24)\Omega_s(\text{R}_2\text{NO}\cdot) \\ & + (-0.68 \pm 0.01)\Omega_s(\text{U}\cdot) \\ & + (3.45 \pm 0.07) \end{aligned} \quad (4)$$

correlation coefficient:  $r = 0.93$

We can assume that the steric effect of the nitroxide and the carbon-centered radicals is the main factor controlling the reactivity of the NRT reaction if the carbon-centered radicals are not resonance stabilized. Poor correlation for the whole set of experimental data (Fig. 2) comes from neglect of the contribution of resonance stabilization of conjugated radicals in the correlation analysis. Comparing the determined regression coefficients  $a$  and  $b$  in eq. (4), the size of the nitroxide seems to be a more dominant steric factor. The larger negative value ( $-2.46$ ) of the regression coefficient  $a$  than  $b$  ( $-0.68$ ) in eq. (4) indicates a larger retardation effect by steric hindrance of nitroxide radicals.

**TABLE II.**  
Parameter for Evaluating the Extent of Resonance Stabilization  $\rho(\text{U}\cdot)$  of Carbon-Centered Radicals.

	Radical $\text{U}\cdot$	$\rho(\text{U}\cdot)$
4 $\cdot$	$\text{H}_2\text{C}\dot{\text{C}}\text{H}_2\dot{\text{C}}\text{H}$	0.53
10 $\cdot$	$\text{C}_6\text{H}_5\dot{\text{C}}\text{H}_2$	0.36
11 $\cdot$	1-Naphthyl- $\dot{\text{C}}\text{H}_2$	0.28
12 $\cdot$	2-Naphthyl- $\dot{\text{C}}\text{H}_2$	0.13
13 $\cdot$	$\text{C}_6\text{H}_5\dot{\text{C}}\text{HCH}_3$	0.53
14 $\cdot$	$\text{C}_6\text{H}_5\dot{\text{C}}\text{HCH}=\text{C}(\text{CH}_3)_2$	0.17
15 $\cdot$	$\text{C}_6\text{H}_5\dot{\text{C}}\text{HCHCH}_2\dot{\text{C}}\text{H}_2$	0.20
16 $\cdot$	$\text{C}_6\text{H}_5\dot{\text{C}}(\text{CH}_3)_2$	0.42
17 $\cdot$	$(\text{C}_6\text{H}_5)_2\dot{\text{C}}\text{H}$	0.37
18 $\cdot$	$(\text{C}_6\text{H}_5)_2\dot{\text{C}}\text{CH}_3$	0.43
19 $\cdot$	$(\text{C}_6\text{H}_5)_2\dot{\text{C}}\text{CH}_2\text{OC}(\text{HC}_3)_3$	0.36
20 $\cdot$	$(\text{C}_6\text{H}_5)_3\dot{\text{C}}$	0.28

#### MULTIPLE CORRELATION ANALYSIS BY USING STERIC $\Omega_s(\text{R}_2\text{NO}\cdot)$ , $\Omega_s(\text{U}\cdot)$ PARAMETERS AND RESONANCE STABILIZATION PARAMETER $\rho(\text{U}\cdot)$ OF CARBON-CENTERED RADICALS

The extent of resonance stabilization of the conjugated carbon-centered radicals (4 $\cdot$ , 10 $\cdot$ , 11 $\cdot$ , 12 $\cdot$ , 13 $\cdot$ , 14 $\cdot$ , 15 $\cdot$ , 16 $\cdot$ , 17 $\cdot$ , 18 $\cdot$ , 19 $\cdot$ , 20 $\cdot$  radicals listed in Table I) should be considered to be closely correlated with the spin densities of their radical center atoms. Thus, the  $\rho(\text{U}\cdot)$  value qualitatively estimated by the PM3 UHF molecular orbital calculations was used as a parameter, which stands for resonance stabilization. It was derived from eq. (5):

$$\rho(\text{U}\cdot) = |\text{SD}(c)| / \sum |\text{SD}(i)| \quad (5)$$

where  $\text{SD}(c)$  and  $\text{SD}(i)$  refer to the calculated spin density on the radical center and on individual carbon atom in the radicals, respectively. As the calculated spin density can take positive and negative values in the UHF calculations, absolute values were used to estimate the resonance-stabilization parameter  $\rho(\text{U}\cdot)$ . The determined  $\rho(\text{U}\cdot)$  are shown in Table II, where the values range from 0.13 to 0.53. Although the  $\rho(\text{U}\cdot)$  parameters used to estimate the extent of resonance stabilization are qualitative, the correlation for the regression of correlation eq. (3) was improved. The correlation coefficient ( $r$ ) for the 57 kinetic data for the NRT

reaction was 0.912, and the correlation equation expressed as:

$$\log k_T = -4.74 \Omega_s(\text{R}_2\text{NO}\cdot) - 1.00 \Omega_s(\text{U}\cdot) + 1.24 \rho(\text{U}\cdot) + 3.36 \quad (6)$$

where the standard deviations of the regression coefficients  $a$ ,  $b$ ,  $c$ , and  $d$  of eq. (3) are 0.56, 0.20, 0.09, and 0.23, respectively.

The values of the regression coefficients  $a$ ,  $b$ , and  $c$  seem to reflect the relative importance of steric and resonance stabilization effects on reactivity in the NRT reaction. Thus, the larger negative coefficient value ( $a = -4.74$ ) indicates that the size of the nitroxide has more of a retarding effect than the carbon-centered radical ( $b = -1.00$ ) in the NRT reaction. The positive value (1.24) of coefficient  $c$  for the  $\rho(\text{U}\cdot)$  parameter suggests that the larger spin density value on the reaction center atom should lead to a higher reactivity for the coupling with the nitroxide. Judging from the results of the correlation analysis using the steric parameter  $\Omega_s$  of the nitroxide ( $\text{R}_2\text{NO}\cdot$ ), the carbon-centered radical ( $\text{U}\cdot$ ), and the resonance stabilization parameter  $\rho(\text{U}\cdot)$ , these parameters seem to be evaluated well as a whole because the rate constant,  $k_T$ , of the NRT reaction may be correlated well by eq. (3) with a correlation coefficient of  $r = 0.912$ . As it is otherwise very difficult to determine the rate constant of the radical reactions, the  $\Omega_s$  steric parameter for the nitroxide and the carbon-centered radical are useful in evaluating the steric effect of these radicals.  $\Omega_s$  can be determined easily within the practical cpu time for any radical molecules used routinely in chemical laboratories by taking advantage of the speed and accuracy of molecular mechanics. As for the resonance stabilization parameter,  $\rho(\text{U}\cdot)$ , further study seems necessary because this parameter is imperfectly quantitatively and used only tentatively in this study.

## Conclusion

The steric substituent parameter,  $\Omega_s$ , which can be determined on the basis of optimized geometries and conformational energies calculated by molecular mechanics, is shown to be a useful parameter for estimating the steric effect of radical species, as well as for the diamagnetic organic compounds. The reactivity in the NRT reaction could be evaluated easily by correlation analysis in

terms of the  $\Omega_s$  of nitroxide radicals,  $\Omega_s(R_2NO\cdot)$ , and carbon-centered radicals,  $\Omega_s(U\cdot)$ , with the resonance stabilization parameter of carbon-centered radicals,  $\rho(U\cdot)$ .

## Calculations

The optimized geometries of the carbon-centered radicals were calculated by the MM3(92) program with the full matrix minimization method. The structure of the nitroxides were optimized by the MM2(91) program. By using the optimized geometries and the conformational energy of the stable conformers of these radicals, the steric substituent parameters,  $\Omega_s$ , of these radicals were calculated using the OMEGAS90 program. UHF semiempirical molecular orbital calculations were carried out with the MOPAC 6 program. All calculations were performed on the Sun SPARCstation IPC.

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